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The University of California
Space Sciences Laboratory

and

Lawrence Berkeley Laboratory
Berkeley, California 94720

Semi-Annual Report

HEAVY ION FRAGMENTATION EXPERIMENTS AT THE BEVATRON

NASA Grant NGR 05-003-513

Principal Investigator
Dr. Harry H. Heckman

Period Covered

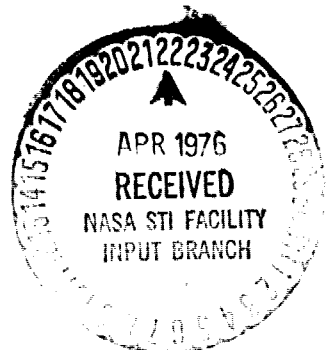1 October 1975 to 31 March 1976

April 16, 1976

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ABSTRACT

This report describes the continued collaborative research effort between the University of California Space Sciences Laboratory and the Lawrence Berkeley Laboratory to study the fragmentation processes of heavy nuclei in matter using heavy-ion beams of the Bevatron/Bevalac. The purpose of the research program is to obtain the single-particle inclusive spectra of secondary nuclei produced at 0° by the fragmentation of heavy ion beam projectiles. The process being examined is $B+T \rightarrow F +$ anything, where $\underline{B}$ is the beam nucleus, $\underline{T}$ is the target nucleus, and $\underline{F}$ is the detected fragment. The fragments $\underline{F}$ are isotopically identified by experimental procedures involving magnetic analysis, energy loss and time-of-flight measurements. In progress are measurements of the partial differential cross-sections for all nuclides (p, ^{4}He, ^{10}Be,....., etc) produced at 0 ± 12.5 mrad by the fragmentation of beam particles ^{12}C,^{14}N,^{15}N,^{16}O and ^{40}Ar as a function of energy,$1.05 \leq E \leq 2.1$ GeV/nucleon,and mass number A of target nucleus.

The principal objectives of the experiment are: a) to study the fragmentation processes of heavy nuclei in matter, b) to measure the total and partial production cross section for all isotopes, c) to test the applicability of high-energy multi-particle interaction theory to nuclear fragmentation, d) to apply the cross-section data and fragmentation probabilities to cosmic ray transport theory and e) to search for systematic behavior of fragment production as a means to improve existing semi-empirical theories of cross-sections.

An activity that is becoming increasingly important in our research activities is the use of our 0-degree magnetic spectrometer by NASA-supported experimenters for the purposes of calibrating cosmic-ray detectors. To support such experiments, we are increasing the capability of the spectrometer system to perform for user groups on-line graphics, data collection and diagnostics using a (GT-40) Graphic Terminal combined with linked PDP 11/45 and 11/20 computers.

HEAVY ION FRAGMENTATION EXPERIMENTS AT HIGH ENERGY

I. INTRODUCTION

This report describes our efforts during the period 1 October 1975 to 31 March 1976, under NASA Grant NGR 05-003-513, in the research program to study the nuclear interactions of relativistic heavy nuclei in the laboratory. This program is being performed at the Bevalac, and is a collaborative effort between the University of California Space Sciences Laboratory and the Lawrence Berkeley Laboratory. The ability of the Bevalac to accelerate heavy ions to energies up to 2.6 GeV/nucleon affords us the opportunity to explore a field of research important to cosmic-ray physics, high-energy-particle physics and nuclear physics. A fundamental problem of cosmic rays is the establishment of the age and source composition of the galactic cosmic rays. The heavy-ion component of this radiation offers one of the best clues for the understanding of this question—provided the pertinent fragmentation cross sections for interaction with interstellar matter are known. The principal objective of this research is to measure these fragmentation cross sections for a variety of beam nuclei, such as ^{12}C, ^{14}N, and ^{16}O, $1.05 \le E \le 2.1$ Gev/nucleon, in various targets H through Pb.

The method of the experiment is to obtain the single-particle-inclusive spectra of secondary nuclei produced at 0° by the fragmentation of heavy ion beam projectiles. The process being examined is $B+T \to F+$ ----, where B is the beam nucleus, T is the target nucleus, and F is the detected fragment. The fragments F are isotopically identified by experimental procedures involving magnetic analysis, energy loss and time-of-flight measurements. Being measured are the production cross-sections for all nuclides (p, ^4He, ^{10}Be,...., etc.) produced at 0 ± 12.5 mrad by the fragmentation of beam particles ^{12}C, ^{14}N, ^{15}N, ^{16}O and ^{40}Ar as a function of energy and mass number A of target nucleus. The fragmentation data for ^{12}C and ^{16}O have been analyzed and published. The N and Ar experiments are now in their data-reduction phase.

II. PURPOSES AND OBJECTIVES OF THE RESEARCH PROGRAM

The specific purpose of the program is to carry out experiments on the single-particle-inclusive spectra of the nuclei produced at 0° by the fragmentation of high energy, heavy-ion beam projectiles. The process we are considering is B+T→F+ anything, where B is the beam (projectile) nucleus, T is the target nucleus, and F is the detected fragment. The purposes of the experiment in progress are:

1) To measure the total fragmentation cross sections for beam nuclei, such as ^{12}C, ^{14}N and ^{16}O, as a function of energy, $1.05 \leq E \leq 2.1$ GeV/nucleon, and mass number A of the target nucleus. In addition, similar measurements may be done using isotopically identified secondary beams of stable and radioactive fragmentation products of the primary beam. Such nuclei will include isotopes of Li, Be, B and C. Target materials range from hydrogen (A=1) to Pb (A=207).

2) To measure the partial differential cross sections for the production of all nuclides (p, ^{4}He, ^{10}Be, ^{11}C, ..., etc.) produced at ±12.5 mrad. by the fragmentation of primary beam particles and their dependences on energy and target nucleus.

The objectives of the experimental program are:

1) To test experimentally the concepts of limiting fragmentation and the factorization of cross-sections when applied to hadron-hadron systems with large baryon numbers; namely, that the fragmentation cross sections attain asymptotic (constant) values at high energies, and the modes of fragmentation are independent of the target-nucleus.

2) To determine the transverse and longitudinal momentum distributions that are

    characteristic of the fragmentation process (e.g., internal motion, final

    state interactions, etc.,) for each isotope F (A,Z) produced in the fragmenta-

    tion of beam projectile B (A,Z).

3) To search for the possible existence of exotic "proton-rich" light nuclei, that

    may be produced in fragmentation of beam nuclei.

4) To search for systematic behavior of fragment production as a means to improve

    existing semi-empirical theories of cross-sections.

5) To apply the cross section data and fragmentation probabilities of the light and

    medium nuclei to the problem of the transformation of cosmic ray nuclei by

    collisions with interstellar hydrogen and helium nuclei.

6) To compare and interpret the observed fragmentation modes of nuclei and the

    isotope-production cross sections with theoretical models based on, for example,

    nuclear cascade theory, Glauber theory, the shell model, etc.

III. SEMI-ANNUAL REPORT

A. Status of Investigation

During this report period our investigations on the fragmentation of relativistic nuclei has continued and extended our work on the 0° - fragmentation of projectile nuclei at 2.1 GeV/nuclei.[1-5] The 0°- heavy-ion magnetic spectrometer that has been used to carry out the fragmentation experiments is now undergoing major changes and improvements in its computer-control capabilities. The spectrometer focuses magnetically-analysed beam fragments, produced within 12.5 mr of the beam direction, onto charge-measuring solid-state detector telescopes placed along the focal plane of the spectrometer. A detailed description of the spectrometer facility and its applicability to calibration experiments is given in Ref. 6.

To date, experimental data on the fragmentation of $^{12}C, ^{14}N, ^{15}N, ^{16}O$ and ^{40}Ar beams at 2.1 GeV/n and ^{12}C at 1.05 GeV/n have been collected. The analysis of the ^{12}C and ^{16}O has been completed, and the experimental results have been published or have been submitted for publication.[2,3,7] A summary of our results are outlined below.

Summary of Results.

i) Within the momentum range allowed by our magnetic spectrometer, the fragmentation of high-energy beam projectiles produces all known isotopes having mass numbers A equal to, or less than, that of the projectile.

ii) The longitudinal momentum distributions of the nuclear fragments in the rest frame of the (moving) projectile are Gaussian shaped, with S. D. widths 50 to 200 MeV/c. The widths are dependent on the projectile and fragment, but independent of target mass (H through Pb) and beam energy.[3]

iii)   464 partial-production cross sections for 35 isotopes have been measured -- a 20 fold increase in the known heavy-ion fragmentation cross sections data above 1 GeV/n.[2]

iv)   The cross sections are energy independent and are factorable into beam (B) -fragment (F) and target (T) terms, e.g., $\sigma_{BT}^F = \gamma_B^F \gamma_T$, where σ_{BT}^F is the cross section of the reaction B+T→F + ▪ --. The quantity γ_T is the target factor. To an accuracy of about 10%, $\sigma_{BT}^F = \sigma_{BH}^F A_T^{\frac{1}{4}}$, i.e., the cross section for the production of fragment F is the product of the cross section for the production of the fragment F in hydrogen and $A_T^{\frac{1}{4}}$, where A_T is the mass number of the target nucleus.[2]

v)   An exception of strict factorization occurs for single-nucleon stripping in high-Z targets. These particular fragmentation cross sections include a component for Coulomb dissociation of the projectile via the target's virtual photon field. This is the first observation of this relativistic effect that has led to a quantitative estimate of Coulomb-induced fragmentation cross sections for high-energy nuclei. Appendix I gives a more detailed discussion of this work.

B.   Applications to Cosmic Ray Physics

The field of cosmic ray physics stands to benefit most immediately from heavy ion research. Dramatic advances in our knowledge of the elemental and isotopic composition of the cosmic rays in the interstellar medium have been made from recent balloon and satellite experiments, and theoretical-computational techniques to interpret these observations in terms of transport equations are available. However, the gross lack of interaction and fragmentation cross sections of cosmic ray nuclei with the interstellar gas necessary for solving the transport problem precludes an understanding of the primordial composition of the cosmic rays. It is, in fact, the lack of comprehensive laboratory data on the fragmentation cross sections that has become a principal impediment to progress in this area of cosmic-ray research. Knowledge of the cross sections for the nuclear transformations of

cosmic ray nuclei will lead to information on the primordial composition itself, while imposing constraints on source models. To retrieve this abundance of astrophysical information will require accurate fragmentation cross sections. The experimental results outlined above is a strong testament that our current project can, and shall, yield this cross section information.

C. NASA Related Research and Instrumentation Development at the Bevalac

An important application of the spectrometer facility used for our fragmentation experiments is the development and calibration of cosmic-ray detectors essential to NASA's Cosmic-ray program. Because the heavy-ion spectrometer makes available beams of any isotope of mass less than the incident beam (provided it is particle stable), its use by NASA experimenters has greatly enhanced the value of the facility. The use of the Bevalac and spectrometer by NASA personnel has been increasing rapidly during the past year, with three major calibrations experiments having been performed during this report period. We tabulate below the actual use of the heavy-ion spectrometer by NASA projects during the past 2 1/2 years of this Grant. Listed are the experiment number, investigator, institution and beam time used.

Experiment No.	Investigator	Institution	Beam Time(hrs)
227 H	Price	UC Berkeley	26
H 30	Price	UC Berkeley	88
H 37	Teegarden	NASA Goddard	15
H 38	Rio	Etude. Nuc. de Saclay	205
H 39	Arens	GSFC	16
H 41	Cartwright	UC Berkeley	21
164 H	Huggett	Louisiana State Univ.	10
165 H	Verma	Louisiana State Univ.	35
H 25	Stone	Cal. Tech.	35
H 16	Greiner	SSL-LBL	31
H 26	Koch	Etude. Nuc. de Saclay	89
H 27	Smith	UC-SSL	58
H 32	Simpson	Univ. of Chicago	15
313 H	Stone	Cal. Tech.	45
246 H	Waddington	Univ. of Minn.	30

Total 719 hrs.

Beam time already requested for calibration runs for calendar dates later then April 1976 are listed below.

Experiment No.	Investigator	Institution	Beam time Requested (hrs)
H 32 (extension)	Simpson	Univ. of Chicago	62
H 41	Cartwright	UC Berkeley	--
202 H	Verma	Louisiana State Univ.	87
261 H	Price	UC Berkeley	--
313 H (extension)	Stone	Cal. Tech.	72
	Von Rosenvinge	NASA Goddard	72
	Webber	Univ. of Hampshire	16
333 H	Metzger	JPL	120
337 H	Israel	Wash. Univ.	40
337 H	Greiner	UCSSL	100
342 H	Stone	Cal. Tech.	92
354 H	Teegarden	GSFC/Ca. Tech.	24
		Total	685

Under this Grant we support these experiments by tuning and delivering the beam type and energy desired by the investigators. This involves the assistance of physicists, electronics engineers and programmers. One hundred percent dedication of the effort supported by this Grant is used to operate the spectrometer facility in support of the NASA experiments. To relate support-effort to beam time, 8-hours of beam time (run and tune-up) requires 2-3 man-days of support, supplied in part by this Grant.

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APPENDIX I

COULOMB DISSOCIATION OF RELATIVISTIC ^{12}C AND ^{16}O NUCLEI[*]

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ABSTRACT

Cross sections for the dissociation of relativistic ^{12}C and ^{16}O nuclei by the Coulomb fields of target nuclei have been measured at the Bevatron. Coulomb contributions to the total fragmentation cross sections are interpreted by the Weizsäcker-Williams method. The minimum-impact parameters deduced from the measured cross sections are characterized by radial overlap distances comparable to the charge-skin thicknesses of the interacting nuclei, compatible with the effects of nuclear absorption.

We report in this Letter experimental evidence for the
dissociation of Bevatron/Bevalac beams of ^{12}C and ^{16}O in the nuclear
Coulomb fields of target nuclei. This evidence comes from experiments
on the target dependence of the isotopic production cross sections for
secondary nuclei produced by the fragmentation of ^{12}C and ^{16}O beam
nuclei at energies E=1.05 GeV/n (^{12}C) and 2.1 GeV/n (^{12}C and ^{16}O).[1]
By use of photonuclear cross-section data and the Weizsäcker-Williams (WW)
method of virtual quanta,[2,3] we are able to account for the measured
cross sections and to determine the minimum impact parameters for Coulomb-
dissociation of heavy-ion projectiles.

Lindstrom et al.[1] have measured the isotopic production
cross section σ_{BT}^{F} for the single-particle inclusive reaction B+T → F+... ,
where B, T, and F are the beam, target, and fragment nuclei, respectively.
Essential to our analysis is that the cross sections σ_{BT}^{F} are factorable,
i.e., $\sigma_{BT}^{F} = \gamma_{B}^{F} \bar{\gamma}_{T}$, where γ_{B}^{F} is dependent on B and F only, and $\bar{\gamma}_{T}$ is the
target factor. Given in Ref. 1 are the measured cross sections σ_{BT}^{F} and
the factored quantities γ_{B}^{F} and $\bar{\gamma}_{T}$ for all isotopes produced by the
fragmentation of ^{12}C and ^{16}O projectiles in H, Be, C, Al, Cu, Ag, and Pb
targets. Plotted in Fig. 1 are the target factors $\gamma_{T} = \sigma_{BT}^{F} / \gamma_{B}^{F}$ versus
target mass A_{T}(AMU). For fragment nuclei with mass $A_{F} \leq A_{B} - 2$, i.e., at
least two nucleons are removed from the beam projectile, all isotopic
production cross sections, for a given target, are interrelated by a
unique target factor, $\bar{\gamma}_{T}$. Striking deviations of γ_{T} from $\bar{\gamma}_{T}$, up to
30 percent in Pb, are observed for those fragmentation cross sections

that involve the loss of one nucleon from the projectile. The differences between the observed values of γ_T and $\bar{\gamma}_T$ increase approximately as Z_T^2 of the target, indicative of a Coulomb effect. We therefore attribute the target factors $\bar{\gamma}_T$ to nuclear fragmentation and the Z_T-dependent differences between γ_T and $\bar{\gamma}_T$ for fragments with mass $A_F = A_B - 1$ to Coulomb dissociation. The experimental Coulomb-dissociation cross sections are therefore defined as $\sigma_{WW}(\exp) = \sigma_{BT}^F - \gamma_B^F \bar{\gamma}_T$, the difference between the measured and factored cross sections.

Jackson[2] presents a classical development of the Weizsäcker-Williams method of virtual quanta for point charges moving at relativistic velocities. Jäckle and Pilkuhn[3] have extended the validity of the Weizsäcker-Williams formula to nonrelativistic energies, and have incorporated nuclear absorption and charge form factors in the theory. The present analysis refines the work of Artru and Yodh,[4] who applied Jackson's treatment of the Weizsäcker-Williams method to estimate the cross sections for Coulomb dissociation of relativistic nuclei.

To the extent that $N(\omega)$, the equivalent number of virtual photons per MeV, is the same for all electric and magnetic multipoles,[5] the Weizsäcker-Williams cross section for the dissociation of a nucleus, at velocity β, by the Coulomb field of a target nucleus, atomic number Z, is given by

$$\sigma_{WW} = \int_{\omega_0} \sigma_\nu(\omega) \, N(\omega) \, d\omega , \qquad (1)$$

where $\sigma_\nu(\omega)$ is the measured photonuclear cross section at photon energy ω.

The number density of virtual photons has the functional form $N(\omega)=(Z^2/\omega\beta^2)F(\beta,\omega b_{min}/\beta\gamma)$, where b_{min}, the minimum-impact parameter, is the only adjustable parameter in σ_{WW}.

References to the photoneutron and photoproton cross sections we used to compute σ_{WW} are, for ^{12}C: $\sigma(\gamma,n)$,[6] $\sigma(\gamma,p)$,[6,7] and for ^{16}O: $\sigma(\gamma,n)$,[8] $\sigma(\gamma,p)$.[9] The cross section $\sigma(\gamma,p)$ for ^{12}C was obtained from the difference between $\sigma(\gamma,total)$[7] and $\sigma(\gamma,n)$.[6] The cross-section data given in Refs. 10-14 were used to extrapolate $\sigma_\nu(\omega)$ to higher values of ω_{max} (to 65 MeV for ^{12}C, 62 MeV for ^{16}O). Because the shape of the high-energy tail of $\sigma_\nu(\omega)$ has little effect on σ_{WW}, we have taken the extrapolated values of the cross sections to be constant.

The giant dipole resonance dominates the photonuclear reaction in the photon-energy interval from about 15 MeV (threshold) to 30 MeV. The photo-dissociation of ^{12}C and ^{16}O proceeds mainly by single-nucleon emission. Furthermore, contributions to σ_{WW} from the higher-threshold multinucleon-loss photoreactions are suppressed by the ω^{-1} weighting [from $N(\omega)$] of $\sigma_\nu(\omega)$ in Eq. (1). The experimental observation that only the single-nucleon-loss fragmentation cross sections exhibit significant deviations from strict factorization in high-Z targets is thus in accord with the process of Coulomb excitation and dissociation.

By equating $\sigma_{WW}(exp)$ to σ_{WW}, Eq. (1) we have determined the impact parameter b_{min} appropriate for each cross section. The minimum-impact parameter is defined by the relation $b_{min}=r_{0.1}^B+r_{0.1}^T-d$, where the $r_{0.1}$'s are the 10 percent charge-density radii of the beam and target

nuclei,[15] and d is the radial-overlap distance. The values of b_{min}
obtained in this experiment are, to within the accuracy of the data,
confined to a limited range in d. Presented in Fig. 2ab, then, are
histograms of the overlap-distances d that account for the experimental
cross sections σ_{WW}(exp) for ^{12}C and ^{16}O projectiles in Ag and Pb targets.
Because of the differences in the theory for the spectra of virtual
quanta, we present two distributions for d, each based upon the expressions
for $N(\omega)$, hence σ_{WW}, given by a) Jackson[2] and b) Jäckle and Pilkuhn.[3]

The standard deviations of the d-distributions are compatible
with the statistical errors in σ_{WW}(exp). Systematic variations in σ_{WW} (exp)
are expected to be small, since the cross sections are obtained from quanti-
ties that are insensitive to errors in beam monitoring, background, focusing
corrections, etc. Possible systematic errors in $d(b_{min})$, other than those
from the theoretical differences in σ_{WW}, are the photonuclear cross sections
$\sigma_v(\omega)$ and those inherent in the method used to extract σ_{WW}(exp) from σ_{BT}^F.
On the average, a 12 percent change in $\sigma_v(\omega)$, a typical uncertainty in the
photonuclear cross-section data, leads to a 1-fm change in $d(b_{min})$.

The unweighted mean (and its statistical error) of the d-dis-
tributions are $\bar{d}=0.4\pm0.8$ fm (Jackson) and 3.0 ± 0.6 fm (Jäckle and Pilkuhn).
These mean values are shown in Fig. 2. Also included in this figure is the
interval of overlap distances bounded by $0 \leq d \leq t_B+t_T$, where t_B and t_T are
the charge-skin thicknesses of the beam and target nuclei, which, in this
experiment, range from 1.9 to 2.3 fm.[15]

Fig. 3 presents the cross-section data from this experiment,
σ_{WW}(exp)= $\sigma_{BT}^F - \gamma_B^F \bar{\gamma}_T$, plotted as a function of target mass. Superimposed on
the data are curves of the computed cross sections σ_{WW} (Jäckle and Pilkuhn)
evaluated for a constant overlap distance $\bar{d}=3.0$ fm. [Curves of σ_{WW} (Jackson)

versus A_T evaluated for $\bar{d}=0.4$ fm are indistinguishable from those shown.]

Following Lindstrom et al.,[1] we find that $\bar{\gamma}_T \propto (A_B^{1/3}+A_T^{1/3}-0.8)$ gives an excellent fit to the target factors of σ_{BT}^F for $A_T \geq 12$, as illustrated in Fig. 1. When expressed in terms of $r_{0.1}$, the target factor has the form of an impact parameter, $\bar{\gamma}_T \propto (r_{0.1}^B+r_{0.1}^T-2.0)$, where $r_{0.1}=r_{0.5}+t/2$ and $r_{0.5}=1.18\ A^{1/3}-0.48$.[15] Thus, we find that the effective overlap distance in $\bar{\gamma}_T$ is $d \approx 2.0$ fm, a value that agrees well with the $\bar{d}$'s (0.4 and 3.0 fm) obtained in this analysis.

To summarize our results, all the saliant features of $\sigma_{WW}(exp)$ are attributable to the fragmentation of projectile nuclei by the Coulomb field of the target nucleus. Irrespective of the theoretical model,[2,3] use of the Weizsäcker-Williams method to interpret $\sigma_{WW}(exp)$ correctly accounts for: i) the identification of those isotope-production cross sections that are significantly enhanced by Coulomb dissociation, ii) the target dependence of $\sigma_{WW}(exp)$, and iii) the magnitudes of $\sigma_{WW}(exp)$. The values of b_{min} derived from $\sigma_{WW}(exp)$ limit the radial overlap, d, of the colliding nuclei to distances comparable to their charge-skin thicknesses t, a manifestation of the effects of nuclear absorption. The Coulomb and nuclear fragmentation processes are related by the result that $\bar{d} \approx d'$, which shows that the maximum overlap distance that accounts for Coulomb dissociation is, in essence, tantamount to the nuclear overlap distance required to account for nuclear (direct-interaction) fragmentation.

FOOTNOTES AND REFERENCES

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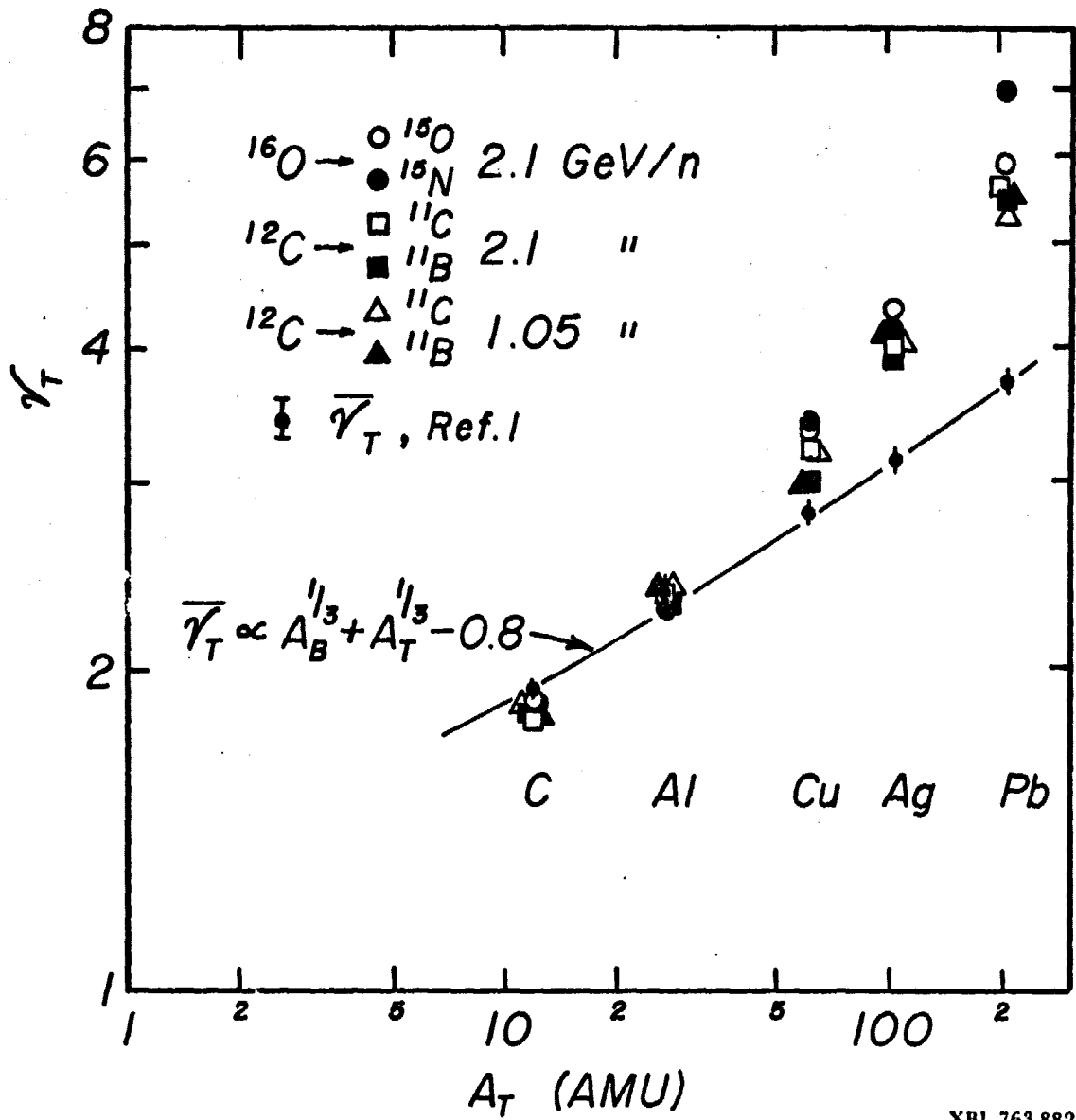
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FIGURE CAPTIONS

Fig. 1. Target factors γ_T plotted versus target mass A_T(AMU), from Lindstrom et al.[1] Individual values of γ_T are shown for the single-nucleon-loss cross sections indicated. The curve $\bar{\gamma}_T \propto A_B^{1/3} + A_T^{1/3} - 0.8$ is drawn through the mean target factors, shown with error bars, for all cross sections σ_{BT}^F, where $A_F \leq A_B - 2$.

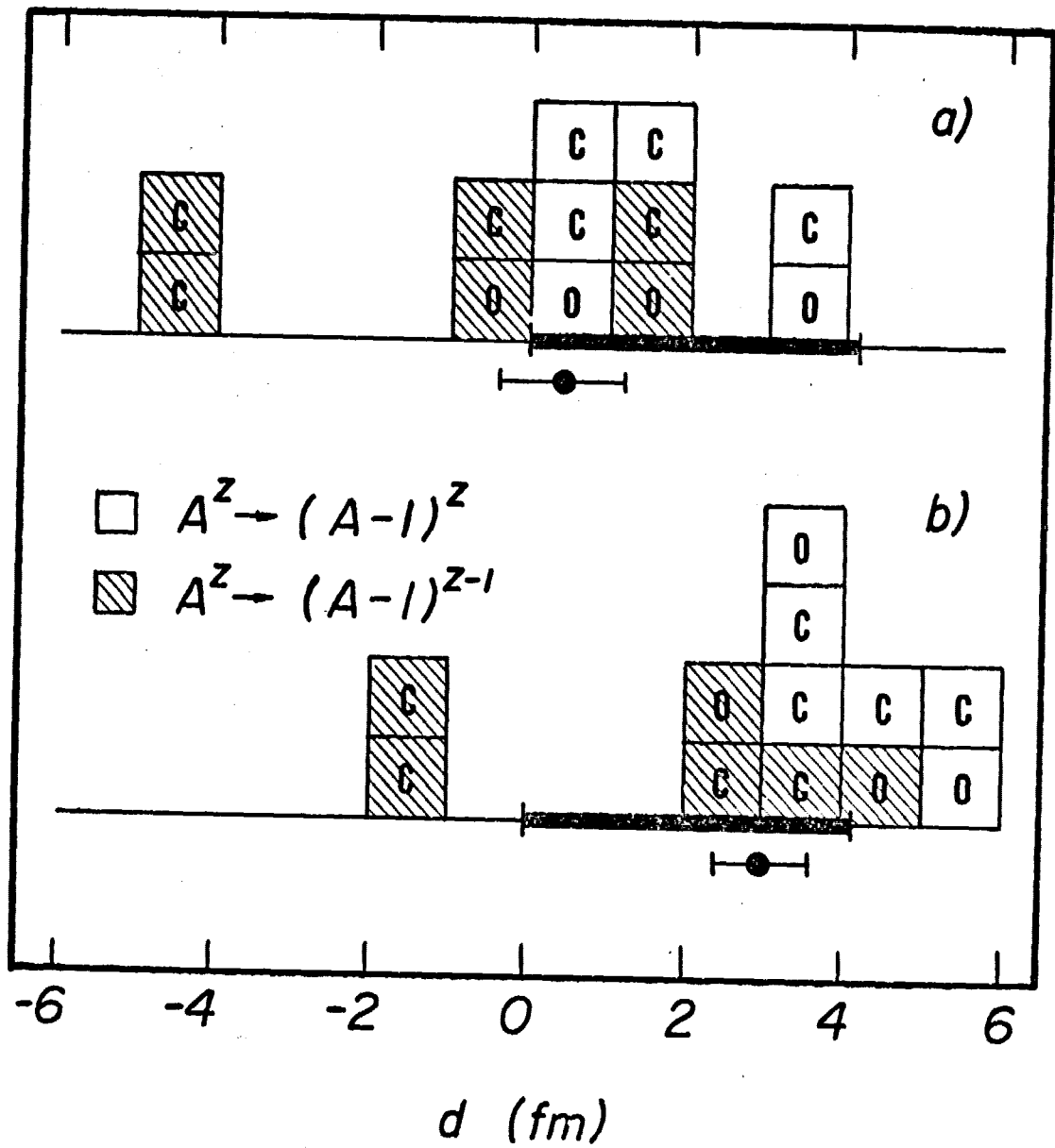Fig. 2. Distributions of overlap distances $d(b_{min})$, and their means, derived from $\sigma_{WW}(exp)$ when fitted to the Weizsäcker-Williams cross sections σ_{WW}, as given by a) Jackson[2] and b) Jäckle and Pilkuhn.[3] The dark horizontal bar delineates the overlap region bounded by $0 \leq d \leq t_B + t_T$, the sum of the charge-skin thicknesses of the beam and target nuclei.

Fig. 3. Target dependence of the measured cross sections $\sigma_{WW}(exp)$ for the Coulomb dissociation reactions indicated. The curves are computed using the Jäckle and Pilkuhn form of σ_{WW} with $\bar{d} = 3.0$ fm.
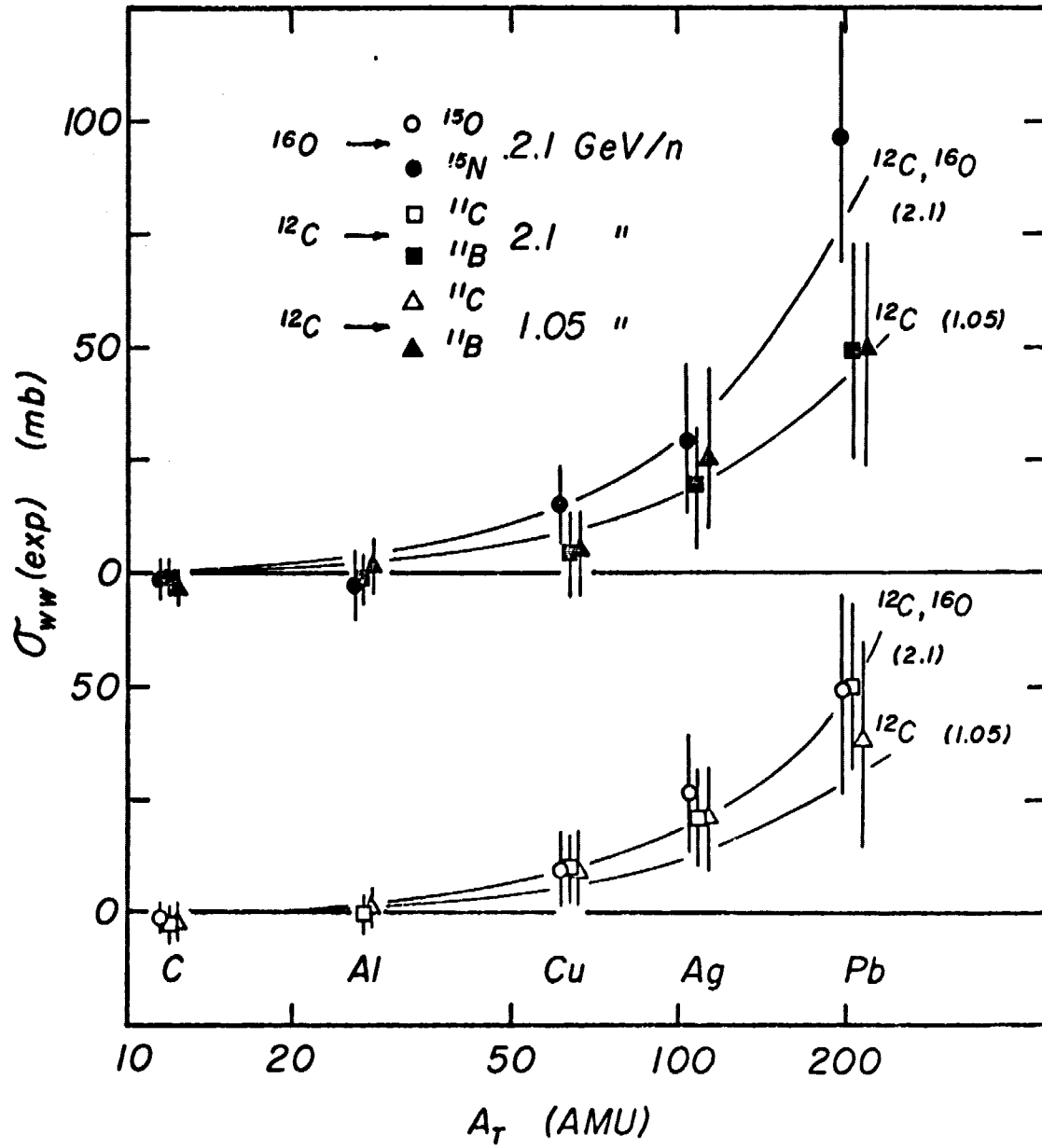
$$\overline{\gamma}_T \propto A_B^{1/3} + A_T^{1/3} - 0.8$$

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Fig. 1

$$A^Z \rightarrow (A-1)^Z$$

$$A^Z \rightarrow (A-1)^{Z-1}$$

$$d \ (fm)$$

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Fig. 2

Fig. 3